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Accounting for regressive eye-movements in models of sentence processing: A reappraisal of the Selective Reanalysis hypothesis

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ABSTRACT

When people read temporarily ambiguous sentences, there is often an increased prevalence of regressive eye-movements launched from the word that resolves the ambiguity. Traditionally, such regressions have been interpreted at least in part as reflecting readers' efforts to re-read and reconfigure earlier material, as exemplified by the Selective Reanalysis hypothesis [Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology, 14*, 178–210]. Within such frameworks it is assumed that the selection of saccadic landing-sites is *linguistically supervised*. As an alternative to this proposal, we consider the possibility (dubbed the Time Out hypothesis) that regression control is partly decoupled from linguistic operations and that landing-sites are instead selected on the basis of low-level spatial properties such as their proximity to the point from which the regressive saccade was launched. Two eye-tracking experiments were conducted to compare the explanatory potential of these two accounts. Experiment 1 manipulated the formatting of linguistically identical sentences and showed, contrary to purely linguistic supervision, that the landing site of the first regression from a critical word was reliably influenced by the physical layout of the text. Experiment 2 used a fixed physical format but manipulated the position in the display at which reanalysis-relevant material was located. Here the results showed a highly reliable linguistic influence on the overall distribution of regression landing sites (though with few effects being apparent on the very first regression). These results are interpreted as reflecting mutually exclusive forms of regression control with fixation sequences being influenced both by spatially constrained, partially decoupled supervision systems as well as by some kind of linguistic guidance. The findings are discussed in relation to existing computational models of eye-movements in reading.

Over the last quarter of a century the field of psycholinguistics has arguably come of age with the development of a wide range of effective, fully-implemented computational models of processes ranging from lexical and oculomotor models of eye movement control in reading (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998), through word reading and pronunciation (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; McClelland & Rumelhart, 1981; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989), auditory word recognition (e.g. McClelland & Elman, 1986; Norris, 1994), speech production (e.g. Dell, 1986), thematic assignment (e.g., McClelland & Kawamoto, 1986; St John & McClelland, 1990) and aspects of language acquisition (Plunkett & Marchman, 1991; Rumelhart & McClelland, 1986).

In contrast with several other areas, in the field of parsing the development of fully-quantified models has been comparatively tentative and it is only in recent years that we have seen the emergence of simulations that are capable of making detailed numerical predictions about the dominant on-line empirical phenomena in the field such

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as the word-by-word or phrase-by-phrase reading times at different points of a sentence (e.g., Christiansen & Chater, 1999; Christiansen & Chater, 2001; Green & Mitchell, 2006; Konieczny & Döring, 2003; Levy, 2008; Lewis, 1993; Lewis & Vasishth, 2005; MacDonald & Christiansen, 2002; McRae, Spivey-Knowlton, & Tanenhaus, 1998; Narayanan & Jurafsky, 2002; Rohde, 2002; Spivey & Tanenhaus, 1998; Stevenson, 1993; Stevenson, 1998; Tabor, Juliano, & Tanenhaus, 1997).

In work on syntactic processing, the experimental evidence comes overwhelmingly from one or other of two on-line methods: self-paced reading (e.g., Altmann & Steedman, 1988; McRae et al., 1998) and eye-tracking (e.g., Ferreira & Clifton, 1986; Frazier & Rayner, 1982; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989). Of these two approaches, the measurement of eye-movements has been the focus of over a hundred published papers in the field (as detailed in an extensive recent review by Clifton, Staub, & Rayner, 2007). Given this wealth of empirical evidence, there are strong pragmatic grounds for using eye-tracking records as one of the primary forms of data for benchmarking and evaluating computational models. In practice, however, it turns out that it has been relatively rare for researchers to fit eye-tracking data. In total, we have only been able to locate seven published papers that use eye-tracking data as a basis for fitting the numerical predictions of computational models of syntactic processing (Binder, Duffy, & Rayner, 2001; Ferretti & McRae, 1999; Just & Carpenter, 1992; Konieczny & Döring, 2003; Spivey & Tanenhaus, 1998; Tanenhaus, Spivey-Knowlton, & Hanna, 2000, and Vasishth, Brüssow, Lewis & Drenhaus, 2008). By way of comparison, there have been at least eleven attempts to model self-paced reading data (e.g., Elman, Hare, & McRae, 2005; Gibson, 1998; Grodner & Gibson, 2005; Hale, 2003; Just & Carpenter, 1992; Lewis & Vasishth, 2005; MacDonald & Christiansen, 2002; McRae et al., 1998; Narayanan & Jurafsky, 2002; Spivey & Tanenhaus, 1998; Tabor et al., 1997).

Given the small body of prior work on modelling eye-movement data (as driven by parsing), it is perhaps not surprising that there are many ground-clearing issues still to be resolved. In relation to parser-generated phenomena, there is as yet no consensus about which of the many standard eye-tracking measures should be made the subject of quantitative predictions. Nor is there any agreement about the nature of the interplay between the forms of control exercised at the syntactic level (and perhaps by other higher level linguistic operations) and those imposed by lexical effects and other similar "low-level" operations. Indeed, the coverage of prior work has been so sparse that there are numerous extensively studied parsing-linked eye-tracking effects that have never been captured by quantitative models. Many of these are linked to the phenomena associated with regressive eye-movements. It is these particular patterns that are the main focus of the present paper.

The challenge of accounting for regressive eye-movements

It has long been known that people very rarely read sentences word by word in the "correct" order. Buswell (1922) reported that for fluent readers approximately 10% of eye-movements are characterized as being *regressive* in the sense that they move back to earlier material rather than passing on to the next unread part of the sentence. Modern estimates, if anything, show slightly greater prevalence of regressive eye-movements with regression rates often reported as being in the range of 10–15% (e.g., Rayner & Pollatsek, 1989, Chapter 4; Rayner, 1998). Based on an analysis of a large corpus of data collected from adults reading a novel, Vitu and McConkie (2000) reported that 15.3% of all saccades were regressive.

There is little doubt that regressions can be triggered by problems encountered at any of the various levels of linguistic analysis from graphemic processing and lexical analysis at one extreme to discourse processing at the higher level. However, it is of particular concern for present purposes that there is solid evidence that regressive eye-movements are associated with difficulties in syntactic processing. For example, regression rates have been shown to increase in the disambiguation regions of sentences (e.g., Frazier & Rayner, 1982; Meseguer, Carreiras, & Clifton, 2002; Rayner, Carlson, & Frazier, 1983; Traxler, Pickering, & Clifton, 1998; Trueswell, Tanenhaus, & Kello, 1993; van Gompel, Pickering, & Traxler, 2001). Partly as a consequence of this, regression-based measures of reading time also increase in such regions (e.g., Brysbaert & Mitchell, 1996; Desmet, De Baecke, & Brysbaert, 2002; van Gompel et al., 2001). Given the pervasiveness of these phenomena, it would be reasonable to expect detailed explanations of regressive eye-movements to feature prominently in the development and evaluation of implemented models of sentence processing. In practice, while one or two studies have taken on the task of modelling measures that *incorporate* regressive fixations (Binder et al., 2001; Konieczny & Döring, 2003), there seems to have been only one study that has responded to the challenge of predicting the prevalence of regressions at different points in a sentence (namely, Tanenhaus et al., 2000). We are not aware of any work at all that has set out to provide syntactically grounded computation-based predictions of the spatial distribution of regressive saccades during sentence processing. With the exceptions listed above and a very recent paper by Reichle, Warren, and McConnell (submitted for publication), all existing computational models of eye-tracking in reading explicitly restrict their machinery to operations below the level of syntactic processing (e.g., Engbert, Longtin, & Kliegl, 2002; Reichle, Rayner, & Pollatsek, 2003; Reilly & Radach, 2003). In effect this makes it impossible for such models to offer any insights into the nature of any interconnection there may be between parsing and eye-movements.

These gaps in our understanding of the full transmission system compromise our ability to use regression data to throw light on the nature of the syntactic operations themselves. While there is a substantial body of work examining the kinds of linguistic operation (termed "reanalysis") assumed to occur at points where regressions are prevalent (e.g., Ferreira & Henderson, 1991; Ferreira & Henderson, 1993; Fodor & Ferreira, 1998; Fodor & Inoue, 1994; Sturt & Crocker, 1998; Sturt, Pickering, & Crocker, 1999; van Dyke & Lewis, 2003), there has been remarkably